Quantitative Infrared Thermography for Quality Control of Concrete Structures Strengthened with FRP Composites

Monica A. Starnes, Nicholas J. Carino, and Eduardo A. Kausel

Synopsis:

The finite-element method is used to carry out parametric analyses on the thermal response of simulated defects in fiber-reinforced polymer (FRP) laminates applied to a concrete substrate. The aim is to assess the potential for quantitative infrared thermography in not only detecting a flaw but also being able to describe its physical characteristics. Three parametric studies are presented, namely: 1) relationship between the thermal input, the maximum signal, and the maximum surface temperature; 2) effects of flaw depth and the number of FRP layers; and 3) effect of flaw width. From these simulations, procedures are established for selecting the thermal input and estimating the flaw depth and width.

Keywords: Fiber reinforced polymer composites, finite element modeling, infrared thermography, nondestructive testing
**Monica A. Starnes** is a graduate student in civil engineering at the Massachusetts Institute of Technology and a researcher at the National Institute of Standards and Technology. Her interests include nondestructive testing, structural rehabilitation, and application of high-performance materials in civil engineering structures.

ACI Fellow **Nicholas J. Carino** is a research structural engineer at the National Institute of Standards and Technology. His research interests include nondestructive testing of concrete, standard test methods, and high-performance concrete. He is a former director of the ACI and currently serves on the Technical Activities Committee and chairs the Specifications Committee.

**Eduardo A. Kausel** is a professor in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology. His research interests are in the areas of structural dynamics, soil dynamics, soil-structure interaction, earthquake engineering, and nondestructive testing.

**INTRODUCTION**

The trend in civil engineering is toward the use of advanced materials such as fiber-reinforced polymer (FRP) composites. Among other purposes, these materials are being used to strengthen existing concrete and masonry structures for rehabilitation purposes, which calls for the use of nondestructive evaluation (NDE) techniques to ensure their correct application and performance.

The best NDE technique needed to detect and characterize a defect depends on the critical size of the defect, the size of the structure being tested, and the environment in which the inspection is carried out. The ideal NDE method in civil engineering applications should be:

- Accurate, reproducible, reliable, robust, and economical;
- Able to inspect large areas as well as localized areas;
- Able to detect critical defect sizes; and
- Non obtrusive to the surrounding environment, and convenient to the users and evaluator of the structure.

Nondestructive testing of thin FRP laminates bonded to concrete or masonry presents a variety of difficulties in the use of the traditional methods developed for inspection of metals due to the anisotropy, variable and non-homogenous composition, non-magnetic properties, and high ultrasonic attenuation of FRP materials. Among the various available techniques, however, infrared thermography offers the greatest potential as a global NDE method, and it has been used successfully to detect defects in FRP laminates bonded to concrete.
Infrared thermography allows localized and global testing of structures, is non-obtrusive and convenient to the users. Technological advancements in uncooled detectors are making infrared thermography a more accurate and economical testing technique than it was in the past.

Current inspection techniques using infrared thermography, however, provide only qualitative assessments of the state of the structure, but give no quantitative information on existing defects. That is, they establish whether a subsurface flaw exists within the FRP-substrate system, but not the depth of the defect or its approximate volume. This qualitative nature of the results stems from the complex relationships between the variables affecting the thermal response of the bonded laminates. The need for defect characterization, not just defect detection, has promoted further research in quantitative infrared thermography.

To enable widespread use of infrared thermography for quantitative assessment of FRP materials applied to concrete and masonry structures, a standard test method is needed. To develop such a standard, however, it is necessary to develop a greater understanding of the factors affecting the thermal response of FRP composites bonded to concrete. The National Institute of Standards and Technology (NIST), in cooperation with the Massachusetts Institute of Technology (MIT), is carrying out research to establish the scientific basis for the development of a standard methodology for using infrared thermography in nondestructive evaluation of concrete and masonry structures strengthened with FRP composites. The goal in this development is to gain an understanding of how the various parameters that may be encountered in infrared thermography testing affect the measured response.

This paper presents the initial results of the NIST/MIT program. First the principles involved in infrared thermography are summarized. Then, the finite-element models used are described. Finally, the effects of the following parameters on thermal response are discussed:

- The amplitude and duration of the thermal input;
- The depth of the flaw (air void); and
- The width of the flaw.

**PRINCIPLES OF HEAT TRANSFER**

Infrared thermography, as a tool for flaw detection, is based on the principle that heat transfer in any material is affected by the presence of subsurface flaws or any other change in thermal properties. Figure 1 is a schematic of a concrete...
substrate with several FRP laminates applied to the surface. There is a flaw within the FRP layer and this flaw affects the flow of heat into and out of the FRP-concrete composite. The difference in heat flow through the flawed and unflawed regions causes localized energy differences on the surface of the test object, which can be measured using an infrared detector or radiometer. Through data processing, the measured infrared radiation is transformed into a surface temperature distribution and recorded in the form of thermograms (isotherm plots). Anomalies in the thermogram indicate the presence of subsurface flaws in the test object. The relation between surface temperature and emitted radiation is based on the Stefan-Boltzmann (Eq. 1) and Wien displacement (Eq. 2) principles (Schlessinger, 1995)

\[ W = e\sigma T^4 \]  
\[ \lambda_{\text{max}} = \frac{b}{T} \]

where,
- \( W \) = radiant intensity (W/m²),
- \( e \) = emissivity of the test object (dimensionless quantity),
- \( \sigma \) = Stefan-Boltzmann constant (5.67x10⁻⁸ W/(m²·K⁴)),
- \( T \) = absolute temperature (K),
- \( \lambda_{\text{max}} \) = wavelength of the maximum radiation intensity (µm), and
- \( b \) = Wien displacement constant (2897 µm/K).

Equation (1) indicates that the emitted radiation is a nonlinear function of temperature, and Eq. (2) indicates that the wavelength of the peak intensity decreases with increasing temperature. At near room temperatures, the wavelength is in the infrared region of the electromagnetic spectrum. The emissivity is a property of the surface and has a value between zero and one. An emissivity value of one is found in perfect emitters such as a black body.

Flaw detection and characterization in civil engineering structures require active infrared thermography, which generally involves transient heat transfer. In addition, defect characterization requires the use of time-resolved infrared thermography. Using this technique, the surface temperature of the test object is monitored and analyzed as a function of time, instead of being monitored at only one particular instant in time. To obtain transient heat transfer, an external thermal stimulus, such as a heating lamp, must be applied to the test object.

Quantitative characterization of internal anomalies by using infrared thermography requires the study of transient heat transfer. Starting with the general case, heat transfer in any material is governed by the theory of diffusion (Lienhard, 1981), the following differential equation:
\[ \nabla \cdot K \nabla T + Q = \rho c \frac{\partial T}{\partial t} \] (3)

where,

- \( \nabla \cdot \) = divergence operator,
- \( K \) = heat conductivity tensor,
- \( \nabla \) = gradient operator,
- \( T \) = temperature,
- \( Q \) = internal heat generation,
- \( \rho \) = density,
- \( c \) = specific heat, and
- \( t \) = time.

If the change in the conductivity tensor is relatively small with respect to the temperature of the material, Eq. (3) simplifies to

\[ K \left( \nabla^2 T \right) + Q = \rho c \frac{\partial T}{\partial t} \] (4)

where \( \nabla^2 \) is the Laplacian operator. In the Cartesian coordinate system, the Laplacian of the temperature is defined as

\[ \nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \] (5)

When heat is applied suddenly to the surface of an object, transient heat flow occurs until thermal equilibrium is reached. During transient heat flow, the temperature at any point in the object changes with time. If the object has large dimensions perpendicular to the direction of uniform heat input and area of uniform heat input large enough compared to measurement depth, heat flows parallel to the input, and the problem is reduced to one-dimensional heat flow. One-dimensional transient heat flow theory states that the temperature within the object changes in a nonlinear manner upon a step change in surface temperature, as follows (Lienhard, 1981):

\[ T_d = T_\infty + (T_i - T_\infty) \text{erf} \left( \frac{y}{2\sqrt{\alpha t}} \right) \] (6)

where,

- \( T_d \) = temperature at any depth \( y \) in the object,
- \( T_\infty \) = applied constant temperature at the surface of the specimen,
- \( T_i \) = initial temperature of the solid,
- \( \text{erf} \) = the Gaussian error function for \( ( \ ) \),
- \( t \) = time, and
- \( \alpha \) = thermal diffusivity of the material.
Thermal diffusivity of a material is defined as

\[ \alpha = \frac{k}{\rho c} \]  

(7)

where,

- \( k \) = thermal conductivity,
- \( \rho \) = density, and
- \( c \) = specific heat.

Thermal diffusivity affects how fast a material changes temperature under transient conditions.

In summary, during transient heat transfer through an object, surface temperature changes caused by internal anomalies in the material are time dependent. Surface temperatures depend on the elapsed time and the type, size, and depth of the defect. The surface temperature distribution is established by measuring the emitted radiation using an infrared camera. Accurate measurement of the surface temperature distribution depends on knowing the value of the emissivity of the surface and on environmental “noise” such as atmospheric attenuation and air movement.

**ANALYTICAL MODELING**

The complexity of transient heat transfer phenomena, involving space and time, is a key obstacle to the development of quantitative infrared thermography. From a theoretical perspective, solutions to transient thermal problems by direct integration of the governing differential equations (Eqs. (4) and (5)) is only possible for the simplest of conditions. The alternative approach is to solve the governing equations using numerical methods, such as the finite-difference method or the finite-element method.

The flexibility of modern numerical algorithms allows the researcher to investigate heat transfer under a variety of conditions, from the relatively simple to the highly complex, provided the proper material properties and boundary conditions are used to create the numerical model. A verified numerical model allows for cost-efficient investigation of the effects of different factors on the thermal response of an object, such as concrete with bonded FRP laminates.

The initial phase of the research is focused on the use of the finite-element method to investigate the parameters affecting the transient thermal response of FRP composites bonded to concrete. In a sense, the finite-element method is used to simulate thermographic testing of FRP laminates bonded to concrete substrates, with and without defects. The results of three parametric studies are presented in this paper. The objectives of the studies are:
• Optimize heating time and intensity for maximum signal;
• Investigate the effect of flaw depth and whether the depth can be estimated from characteristics of the signal; and
• Investigate whether flaw width can be estimated from the characteristics of the signal and establish minimum detectable flaw size.

Simulation Models

Numerical simulations are performed using a general-purpose, finite-element analysis package. The simulated test object consists of a 100 mm wide by 20 mm thick concrete slab covered with several layers of 0.5 mm thick carbon FRP (CFRP) laminates. To reduce computation time, two-dimensional models are used, that is, the test object is infinite in the third dimension. Subsurface flaws of varying depth and size are placed at the center of the model. Internal flaws are simulated as air gaps, representing delaminations, debonds, or concrete spalls depending on their location. Delaminations are gaps located between the FRP laminates, debonds are gaps at the interface between FRP and concrete, and concrete spalls are gaps in the concrete substrate. Because the flaw is located at the centerline of the model, the model is symmetrical about its centerline, and only one half needs to be analyzed. Figure 2 shows the physical model and the model analyzed.

The material properties of the model are those of concrete for the substrate, air for the defect, and CFRP for the bonded composite. The material properties used in the simulations are presented in Table 1. For the FRP, the model simulates a wet lay-up composite system. The material properties of the constituent materials of the FRP (carbon fibers and epoxy resin) are combined to simulate homogeneous but anisotropic laminates. Homogeneity is assumed based on the scale of the problem, macroscopic instead of microscopic. As a result, the material in direct contact with the concrete substrate is the FRP composite. The CFRP laminate in direct contact with the concrete has the fibers running in the x-direction, while each of the adjacent laminates has the fiber direction rotated by 90 degrees.

The finite-element model is composed of four-noded quadrilateral elements. Each node has one degree of freedom, namely the temperature. The model is meshed using the “mapped meshing” feature of the program, which allows the user to directly control the element size and type. The “global” element size is set to 0.5 mm. Mesh refinement is applied to the thin CFRP laminates and at the FRP/concrete interface. In the y-direction, the thickness of each composite laminate is subdivided into 4 elements while the thickness of the flaw is subdivided into 2 elements. The rest of the concrete substrate is meshed using a graded mesh, with a finer mesh at the top and a coarser mesh at the bottom of the specimen. The average thickness of the concrete elements is 2.75 mm with a
“spacing ratio” of 10. The spacing ratio represents the ratio of the thickness of the largest element to the thickness of the smallest element.

For comparison purposes, the same time stepping is used for all the problems. The initial time step is 0.009 s. The automatic time stepping capability of the finite-element software is used with minimum and maximum time steps of 0.008 s and 0.1 s, respectively. A sensitivity analysis was performed to determine an appropriate maximum time step for this particular study. For this purpose, trial simulations were performed using three different maximum time steps, namely 0.009 s, 0.1 s, and 0.5 s. The maximum time step of 0.5 s was found to be too large to fully capture the thermal evolutions of these particular sets of simulations. Maximum time steps of 0.009 s and 0.1 s successfully captured the thermal behavior of the models. The maximum time step of 0.1 s is selected as a balance between computational economy and accuracy. The simulation output (nodal temperatures) is recorded at every time step.

The analysis is defined as a transient heat transfer problem. A square heat pulse of intensity $q$ and duration $\tau$ is applied to the top surface of the model (see Fig. 1). Adiabatic conditions ($dT/dx = 0$ and $dT/dy = 0$) are assumed for the bottom and side surfaces of the model (Fig. 2). This assumption is realistic for the short time durations used in the analyses and the geometry of the simulated flawed test object. The initial temperature for all the simulations is 23 °C, which represents ambient temperature. For simplification, uniform heating, no cooling losses, and perfect contact between layers are assumed for the analyses.

**Thermal Response Parameters**

The surface temperatures at various points above the flaw as well as the “background” temperature at a point where the flaw has no influence are recorded (see Fig. 1) as the output of each analysis. The recorded nodal temperature histories are then used to compute the following parameters:

- Maximum surface temperature;
- The thermal signal;
- The thermal contrast;
- The time to reach maximum signal; and
- The time to maximum contrast.

The maximum surface temperature occurred above the flaw at the end of the thermal pulse. The thermal signal $\Delta T$ is defined as

$$\Delta T = T_{\text{defect}} - T_{\text{background}}$$

where,

$T_{\text{defect}} = \text{temperature at the surface above the flaw, and}$

$T_{\text{background}} = \text{temperature at a point above sound material that is not affected by the flaw.}$
The thermal contrast $C$ is defined as

$$C = \frac{\Delta T}{T_{\text{background}} - T_o}$$  \hspace{1cm} (9)$$

where,

- $\Delta T$ = thermal signal,
- $T_{\text{background}}$ = temperature at a point above sound material that is not affected by the flaw, and
- $T_o$ = initial temperature of the test object.

The thermal signal is the most widely used parameter for detecting subsurface flaws by infrared thermography. Some researchers, however, prefer using the thermal contrast because this normalized value is independent of the amount of heat applied to the specimen, but it depends on the details of the flawed test object. The thermal contrast is analogous to a stress concentration factor in that it indicates the effect of the flaw on magnifying the surface temperature above the flaw.

The time to reach maximum signal $t_s$ and the time to reach maximum contrast $t_c$ are used to investigate the effects of varying the depth of the flaw.

**RESULTS**

**Effect of Thermal Input**

The first parametric study evaluates the effect of the thermal input, which is modeled as a square thermal pulse of amplitude $q$ (W/m$^2$) and duration $\tau$ (s). The values of $q$ and $\tau$ are varied over a wide range. The objective is to determine whether a methodology can be developed for estimating the optimal thermal energy for experimental configurations relevant to civil engineering applications. The pulse durations vary from 0.05 s to 3 s and the applied heat flux varies from 5,000 W/m$^2$ to 100,000 W/m$^2$.

The test object consists of two CFRP laminates bonded to the concrete substrate as described in the previous section. The subsurface flaw is a 0.2 mm thick debond.

Analysis of the response parameters yields interesting results regarding the maximum signal as well as the maximum surface temperature. It is found that the effects of the thermal pulse can be summarized easily if the product of $q$ and $\tau$ are used. The product $\tau \cdot q$ represents the input energy per unit area, that is,

$$E = q \cdot \tau$$  \hspace{1cm} (10)$$
It is found that the maximum signal can be expressed as a linear function of the input energy per unit area, which will be called the “input energy density.” For the particular test object used in this series of analyses, the best-fit empirical relationship is found to be:

$$\Delta T_{\text{max}} = 0.00024 E$$  \hspace{1cm} (11)

Figure 3 illustrates the maximum signal versus input energy density. This figure provides a powerful tool for selecting the thermal input to achieve a desired maximum signal. This tool, however, has a limitation because there are infinite combinations of input heat flux and pulse duration for a specific maximum signal. The differences achieved with the various combinations of $q$ and $\tau$ are the time when the maximum signal is obtained and the maximum surface temperature that is attained.

The maximum surface temperature reached during thermographic testing of FRP bonded to concrete requires special consideration. When the temperature of the resin of the FRP increases above the glass transition temperature, $T_g$, the mechanical properties of the matrix degrade. Glass transition temperatures for CFRP used in civil engineering applications are often on the order of 50 °C (Karbhari et al., 1998; Christensen et al., 1996). Thus the allowable maximum surface temperature is a limiting factor in selecting the thermal input.

The results of the simulations are analyzed next to investigate the relationship between the thermal input and the maximum surface temperature. The analysis indicates that, for a given pulse duration, the maximum surface temperature is a linear function of the input energy density, as follows:

$$T_{\text{max}} = \delta(\tau) E + 23$$  \hspace{1cm} (12)

where,

$$\delta(\tau) = \text{slope of the line for a given pulse duration.}$$

The value of $\delta$ is found to be a nonlinear function of the pulse duration. For short duration pulses, the slope $\delta$ is large and surface temperature increases sharply with the input energy density compared with longer duration pulses. It is found that the slope $\delta$ can be approximated by the following equation:

$$\delta(\tau) = \frac{0.783}{\tau} + 0.192 - 0.076 \tau$$  \hspace{1cm} (13)

Equations (12) and (13) allow the construction of Fig. 4, which shows the maximum surface temperature as a function of input energy density and pulse duration. Figure 4 illustrates that for a required minimum input energy density (as established by the desired $\Delta T_{\text{max}}$) a series of different pulse durations may be
selected. The limiting maximum surface temperature determines the shortest pulse duration that can be used to achieve the desired signal.

In summary, the results of the first parametric study lead to a simple approach for selecting the thermal input to obtain the required maximum signal while limiting the maximum surface temperature. For example, suppose we desire a maximum thermal signal of $\Delta T_{\text{max}}=10\,^\circ\text{C}$. According to Fig. 3, the required input energy density is about 40 kJ/m$^2$. Suppose we desire to limit the surface temperature to 50 $^\circ\text{C}$. Assuming that the initial temperature is 23 $^\circ\text{C}$, Fig. 4 shows that the pulse duration should not be less than 2 s. The required input heat flux will be lower for a longer pulse duration. For a pulse duration of 2 s the required input flux is 20 kW/m$^2$, and for a 3 s pulse duration it is 13.3 kW/m$^2$. Of course, the relationships in Figs. 3 and 4 are only applicable to the specific object used in these simulations.

**Effect of the Depth of the Flaw**

When applying FRP materials to strengthen concrete or masonry structures, defects may arise between the FRP laminates (delaminations) or at the FRP/concrete interface (debonds). In addition, failure planes may occur in the concrete if the shear stresses needed to transfer load to the FRP, exceed the capacity of the concrete (spalls). Thus defects can occur at different depths within the repaired object. It is, therefore, desirable to investigate how the depth of a flaw affects the thermal response and to establish whether it may be feasible to determine the depth of the flaw from the characteristics of the thermal evolution. The term “thermal evolution” refers to the spatial and temporal variation of the surface temperature.

Three test objects, which include 2, 3, or 5 CFRP laminates and flaws, are analyzed. For each test object, the depth of the flaw is varied to include delaminations, debonds, and concrete spalls at different depths. The results reveal that the thermal response is a function of both the thickness of the FRP layer and the depth of the flaw. For the purpose of estimation, a simple procedure is developed to represent the maximum thermal signal and contrast as a function of flaw depth, which is described by the following simple power function:

$$\varepsilon \gamma d^{\varepsilon}$$

where,

- $d$ = depth of the flaw,
- $\gamma$ = empirical coefficient, and
- $\varepsilon$ = empirical exponent.

The time for maximum signal and the time for maximum contrast are selected as the thermal response parameters best suited for correlation with flaw depth. The
best-fitting power functions for the time of maximum signal $t_s$ and the time for maximum contrast $t_c$ are presented in Table 2.

Based on the information obtained from this parametric study, a tentative procedure for estimating the depth of the flaw consists of the following:

- Estimate the thickness of the FRP layer (in mm) by some other technique.
- Estimate the coefficients and exponents (Eq. 14) for time for maximum signal and for time for maximum contrast. For the time for maximum signal, these values can be found from these empirically determined relationships:
  \[
  \gamma_s = 4.849 \left( d_{FRP} \right)^{0.0697} \tag{15}
  \]
  \[
  \varepsilon_s = 0.0816 d_{FRP} + 0.943 \tag{16}
  \]
  For the time for thermal contrast, the coefficients are:
  \[
  \gamma_c = 8.432 \left( d_{FRP} \right)^{0.037} \tag{17}
  \]
  \[
  \varepsilon_c = 0.867 d_{FRP} + 0.852 \tag{18}
  \]
  where,
  - $d_{FRP}$ = thickness of the FRP layer,
  - $\gamma$ = coefficient of the power function in Eq. (14), and
  - $\varepsilon$ = exponent of the power function in Eq. (14).

- The coefficients and exponents determined in the previous step provide the power function equations for the time for maximum signal and time for maximum contrast for flaws at any depth, that is,
  \[
  t_s = \gamma_s d^{\varepsilon_s} \tag{19}
  \]
  \[
  t_c = \gamma_c d^{\varepsilon_c} \tag{20}
  \]
  where,
  - $d$ = depth of the flaw,
  - $t_s$ = time for maximum signal, and
  - $t_c$ = time for maximum contrast.

- Inversion of Eqs. 19 and 20 allows the estimation of the depth of the flaw based on the measured thermal response of the test object.
Since these equations are based on the test objects used in the simulations, experimental verification is needed to establish the reliability of the proposed procedure.

An alternative approach for estimating flaw depth is to use previously established plots of the time for maximum signal as a function of flaw depth, as illustrated in Fig. 5. This procedure is simpler than using the above equations, and it may provide an adequate estimation for the flaw depth. In the example shown in Fig. 5, for a 10 s time for maximum signal, the estimated flaw depth is 1.8 mm for the case of a test object with 5 layers of CFRP, while it is 2.0 mm for a test object with 2 plies of CFRP. For this case, the estimation of flaw depth varies only by 0.2 mm, which is less than the thickness of an FRP layer. For a longer time for maximum signal, say 15 s, the estimated flaw depth is 2.5 mm for the case of 5 layers of CFRP and 2.9 mm for 2 layers of CFRP. The estimated flaw depth varies by only 0.4 mm; again this is less than the thickness of an FRP layer. Thus it may not be necessary to know accurately the thickness of the FRP to estimate the flaw depth.

Effect of the Width of the Flaw

The size of subsurface flaws could be the determining factor on the proper performance of an FRP composite bonded to concrete. With this concern, the International Conference of Building Officials Evaluation Services (ICBO ES 2001) has introduced requirements for the allowable flaw size. Among the conditions of acceptance, the ICBO ES states that small air flaws of diameters up to 3 mm occur naturally in FRP systems. Flaws of this size and smaller do not require repair. Flaws larger than 13 cm² in area, however, should be repaired.

The objectives of the third parametric study are as follows:

- Understand the effect of flaw width on the thermal response;
- Establish a procedure for estimation of flaw width; and
- Determine the minimum width of detectable flaw.

For this part of the study, the assumed thickness of the flaw is 0.1 mm. Flaws ranging from 3.0 mm to 25 mm wide (x-direction) are investigated. The models include three different groups depending on the depth of the flaw: delaminations

\[ d = \exp \left( \frac{\ln(t) - \ln(t_a)}{e_{nn}} \right) \]  

(21)

\[ d = \exp \left( \frac{\ln(t) - \ln(t_a)}{e_{nn}} \right) \]  

(22)
0.5 mm deep, debonds 1.5 mm deep, and concrete spalls 2.5 mm deep. Three layers of CRFP are used as shown in Fig. 6.

Since the investigation aims at estimating the width of the flaw, the surface temperature as a function of distance (the x-coordinate) is considered. Figure 7 illustrates a typical temperature-distance plot. The location of the inflection point illustrated in Fig. 7 is chosen as the basis for estimating the location of the edge of the subsurface flaw. The location of the inflection point may be computed by setting the second derivative of the temperature vs. distance curve equal to zero

$$\frac{\partial^2 T}{\partial x^2} = 0 \text{ at } w_{\text{estimate}}$$

where

- $T_s$ = surface temperature,
- $x$ = distance from the centerline along the x-axis, and
- $w_{\text{estimate}}$ = estimation of the distance of the edge of the flaw from the centerline.

The surface temperature as a function of the distance is recorded at the time of maximum signal for each simulation. The results of the estimation using the location of the inflection point are presented in Table 3. The estimation error computed as

$$\text{error} = w_{\text{estimate}} - w_{\text{actual}}$$

where

- $w_{\text{actual}}$ = actual width of the flaw,

is also presented in Table 3.

The results indicate that the flaw may be underestimated or overestimated depending on the size and depth of the flaw. For example, the width of large flaws tends to be underestimated while the width of smaller flaws tends to be overestimated.

Further analysis indicated that the estimation errors could be expressed as hyperbolic functions as shown in Fig. 8. The figure shows that the error increases with the depth of the flaw, that is, the estimation of delamination width is more accurate than the estimation of debonds or concrete spalls. If flaws larger than 13 cm² in area (36 mm x 36 mm) are a concern (ICBO ES, 2001), the width estimation error of such flaws is smaller than 6%.

An additional issue that needs addressing is the minimum width of detectable flaws. The width of detectable flaws is influenced highly by the thermal sensitivity of the infrared detector or camera and the environmental noise, among others. Thus, calculation of the minimum detectable flaw is based on the required maximum thermal signal.
The minimum detectable flaw is estimated for three different cases: $\Delta T_{\text{max}}$ equal to 0.1 °C, 1.0 °C, and 2.0 °C. The first case, $\Delta T_{\text{max}}$ equal to 0.1 °C, corresponds to the thermal sensitivity of most infrared cameras. Because the values reported by the finite-element analysis are ideal, that is, with perfect layer interfaces and without ambient noise, the cases with $\Delta T_{\text{max}}$ equal to 1.0 °C and 2.0 °C are also considered.

Analysis of the FEM output reveals that the increase in $\Delta T_{\text{max}}$ can be expressed as the following hyperbolic functions of the width of the flaw:

\[
\Delta T_{\text{max}} = 20.95 \frac{0.40(w-1.86)}{1+0.40(w-1.86)}
\] (25)

for delaminations ($d = 0.5$ mm),

\[
\Delta T_{\text{max}} = 5.95 \frac{0.14(w-1.90)}{1+0.14(w-1.90)}
\] (26)

for debonds ($d = 1.5$ mm),

\[
\Delta T_{\text{max}} = 3.12 \frac{0.10(w-1.87)}{1+0.10(w-1.87)}
\] (27)

and for concrete spalls ($d = 2.5$ mm),

Thus, the minimum width of detectable flaws can be computed using Eqs. 28, 29, and 30. The results from the calculations are presented in Fig. 9.

Observation of the results presented in Fig. 9 indicates that as the resolution of the signal increases (smaller $\Delta T_{\text{max}}$), the minimum width for detectable flaws decreases. Power functions can be used to express the minimum width of the detectable flaw as a function of depth. For the case of a thermal resolution of 0.1 °C the minimum width of detectable flaw can be expressed as

\[
w_{\text{min}} = 1.61 + 0.36 d^{0.53}
\] (28)

where

\begin{align*}
  w_{\text{min}} & = \text{the minimum width of detectable flaws, and} \\
  d & = \text{the depth of the flaw in millimeters.}
\end{align*}

For the case of a thermal resolution of 1.0 °C the following power function can be used to estimate the minimum width of detectable flaws:
Finally, for the case of a thermal resolution of 2.0 °C, the following power function estimates the minimum width of detectable flaws:

\[ w_{\text{min}} = 1.86 + 0.61d^{2.27} \]  

(29)

The results indicate that near-the-surface delaminations can easily be detected up to widths of 2 mm. The minimum width required for detection increases with increasing depth. For concrete spalls buried 2.5 mm from the surface, the minimum width varies from 2 mm with \( \Delta T_{\text{max}} = 0.1 \) °C to 20 mm with \( \Delta T_{\text{max}} = 2 \) °C.

CONCLUSIONS

The finite-element method is used to evaluate the effect of several parameters on the thermal response of subsurface flaws in concrete strengthened with FRP composites. The parameters investigated are the thermal input required for flaw detection, the depth of the flaw, and the width of the flaw.

The results indicate that the thermal input can be optimized. Given a specific heat flux, the selection of the pulse duration is governed by the surface temperature that can be tolerated and the required input energy density for the desired signal. For a given flaw geometry, the maximum signal is a linear function of the input energy density \( E \) (J/m²). The maximum surface temperature is a function of the input energy density as well as pulse duration.

The investigation involving the effect of flaw depth leads to a simple procedure for estimating the response parameters as a function of the thickness of the FRP and the depth of the flaw. The procedure developed for the estimation of flaw depth is based on the time for maximum signal.

Finally, both the flaw depth and minimum flaw width required for detection are considered. The results indicate that the minimum flaw width required to detect a flaw increases nonlinearly with increasing depth. The determination of the minimum flaw width is a function of the maximum thermal signal. The required maximum thermal signal depends on the thermal resolution of the infrared detector and the ambient noise due to convection losses among others.

The finite-element simulations indicate that infrared thermography has the potential to be an effective NDT method for quantitatively determining the quality of the bonding of FRP laminates to concrete structures. This analytical research in combination with experimental trials in-progress may provide the
bases for standardization and implementation of quantitative infrared thermography testing in civil engineering structures.

REFERENCES


Table 1 — Material properties used in simulations

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>CFRP (0 degree layer)</th>
<th>CFRP (90 degree layer)</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>2400</td>
<td>1600</td>
<td>1600</td>
<td>1.2</td>
</tr>
<tr>
<td>$c$ (J/kg·K)</td>
<td>800</td>
<td>1200</td>
<td>1200</td>
<td>700</td>
</tr>
<tr>
<td>$k_x$ (W/m·K)</td>
<td>1.5</td>
<td>7</td>
<td>0.8</td>
<td>0.024</td>
</tr>
<tr>
<td>$k_y$ (W/m·K)</td>
<td>1.5</td>
<td>0.8</td>
<td>0.8</td>
<td>0.024</td>
</tr>
<tr>
<td>$k_z$ (W/m·K)</td>
<td>1.5</td>
<td>0.8</td>
<td>7</td>
<td>0.024</td>
</tr>
</tbody>
</table>
Table 2 — Summary for set of FEM simulations involving the investigation of flaw depth
<table>
<thead>
<tr>
<th>Flaw depth (mm)</th>
<th>Actual width (mm)</th>
<th>Estimated width (mm)</th>
<th>Estimation error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>25.0</td>
<td>24.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>0.5</td>
<td>14.0</td>
<td>13.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>0.5</td>
<td>5.0</td>
<td>4.6</td>
<td>-0.4</td>
</tr>
<tr>
<td>0.5</td>
<td>3.0</td>
<td>3.1</td>
<td>+0.1</td>
</tr>
<tr>
<td>1.5</td>
<td>25.0</td>
<td>23.2</td>
<td>-1.8</td>
</tr>
<tr>
<td>1.5</td>
<td>14.0</td>
<td>12.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>1.5</td>
<td>5.0</td>
<td>5.7</td>
<td>+0.7</td>
</tr>
<tr>
<td>1.5</td>
<td>3.0</td>
<td>4.9</td>
<td>+1.9</td>
</tr>
<tr>
<td>2.5</td>
<td>25.0</td>
<td>23.3</td>
<td>-1.7</td>
</tr>
<tr>
<td>2.5</td>
<td>14.0</td>
<td>12.7</td>
<td>-1.3</td>
</tr>
<tr>
<td>2.5</td>
<td>5.0</td>
<td>6.7</td>
<td>+1.7</td>
</tr>
<tr>
<td>2.5</td>
<td>3.0</td>
<td>6.0</td>
<td>+3.0</td>
</tr>
</tbody>
</table>
Heat flux, $q$

Flaw

1

2

$T_1 - T_2$

Time, $t$

Heat flux

$q$

$\tau$

Time, $t$
$\frac{dT}{dx} = 0$

CFRP laminates

Debond

Concrete slab

$\frac{dT}{dy} = 0$

Heat flux

Symmetry

C.L.

50 mm

0.2 mm

12.5 mm

5 mm

5 mm

22
$\tau = 0.1 \text{ s}$

$\tau = 0.2 \text{ s}$

$\tau = 0.4 \text{ s}$

$\tau = 1 \text{ s}$

$\tau = 2 \text{ s}$

$\tau = 3 \text{ s}$

$T_{\text{max}} (C)$

$E (\text{kJ/m}^2)$
Surface temperature (°C)

Distance from centerline (mm)

Inflection point

Estimation of 1/2 width of flaw
Delaminations (0.5 mm deep)
Debonds (1.5 mm deep)
Spalls (2.5 mm deep)
The graph illustrates the relationship between flaw depth (mm) and the minimum width of detectable flaw (mm) for different temperature differences ($\Delta T_{\text{max}}$): 0.1°C, 1.0°C, and 2.0°C.
Quantitative Infrared Thermography for Quality Control of Concrete Structures Strengthened with FRP Composites

Starnes, Carino, and Kausel

LIST OF FIGURES

Fig. 1 Schematic of the infrared thermography method to detect presence of a flaw based on surface temperature differences

Fig. 2 Example of test object used in numerical analysis; the physical model is on the left and the analytical model is on the right

Fig. 3 Maximum signal as a function of input energy density

Fig. 4 Maximum surface temperature as a function of input energy density and pulse duration

Fig. 5 Example of estimation of flaw depth using a pre-established relationship

Fig. 6 Summary of models used in simulations involving variations in flaw width

Fig. 7 Estimation of width of flaw

Fig. 8 Estimation error as a function of flaw width

Fig. 9 Minimum width of detectable flaw as a function of flaw depth